



Energy and CO₂ emissions performance assessment of residential micro-cogeneration systems with dynamic whole-building simulation programs

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ABSTRACT

Micro-cogeneration, also termed micro combined heat and power (MCHP) or residential cogeneration, is an emerging technology with the potential to provide energy efficiency and environmental benefits by reducing primary energy consumption and associated greenhouse gas emissions. The distributed generation nature of the technology also has the potential to reduce losses due to electrical transmission and distribution inefficiencies and to alleviate utility peak demand problems. Detailed MCHP models for whole-building simulation tools, developed in Annex 42 of the International Energy Agency (IEA) Energy Conservation in Buildings and Community Systems Programme, have been used to conduct a performance assessment study for a number of micro-cogeneration systems and residential buildings. Annual non-renewable primary energy (NRPE) demand and CO₂-equivalent (CO₂-eq) emissions were determined by simulation for different cogeneration technologies, namely natural gas-fuelled solid oxide (SOFC) and polymer electrolyte membrane fuel cells, Stirling and internal combustion engines. These were compared to the reference system with a gas boiler and electricity supply from the grid. A ground-coupled heat pump system was also analysed for comparison. The cogeneration units were integrated in single and multi-family houses of different energy standard levels. Two different electricity generation mixes were considered: European mix and combined cycle power plant (CCPP). For the MCHP devices, detailed dynamic component models as well as simplified performance map models were used, developed and calibrated with either results from laboratory experiments or with manufacturer data. The simulations were performed using the whole-building simulation programme TRNSYS, using domestic hot water and electric demand profiles specified in IEA Annex 42. Combinations of three demand levels were analyzed. In NRPE demand, for the European electricity mix, most MCHP systems offered reductions (up to 34%) in comparison with the gas boiler reference system and crediting the electricity exported to the grid. For the CCPP electricity generation mix, the largest NRPE reductions resulted for the ground-coupled heat pump systems (up to 29%). The maximum reduction with a cogeneration system was 14%. In terms of CO₂-eq emissions, most cogeneration systems offered reductions for the European electricity mix (up to 22%). However, maximum reductions resulted for the heat pump system (23%). For the CCPP mix, maximum reductions by far again resulted for the heat pump systems (up to 29%). The maximum reduction for a cogeneration system was achieved with the ICE system in the single-family house (14%).

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1. Introduction

The achievement of sustainability in the building sector necessitates a tremendous effort to reduce energy demand, boost energy

Abbreviations: CCPP, combined-cycle (gas and steam) power plant; CHP, combined heat and power (cogeneration); CO₂-eq, carbon dioxide equivalent; DHW, domestic hot water; FC, fuel cell; GB, gas boiler; HP, heat pump; ICE, internal combustion engine; LHV, lower heating value; MCHP, micro combined heat and power (micro-cogeneration); MFH, multi-family house; NG, natural gas; NRPE, non-renewable primary energy; PA, performance assessment; PI, proportional-integral; PH, Passive House; PE, primary energy; PEMFC, polymer electrolyte membrane fuel cell; SFH, single-family house; SE, Stirling engine; SH, space heating; SOFC, solid oxide fuel cell; UCTE, Union for the Co-ordination of Transmission of Electricity.

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efficiency and increase the share of renewable energy sources. On the demand side, the improvement of the building envelope's insulation, air tightness and fenestration are accepted measures. On the supply side, micro-cogeneration, also termed micro combined heat and power (MCHP) or residential cogeneration, is an emerging technology associated with the potential to reduce primary energy consumption and associated greenhouse gas emissions through the concurrent production of electrical and thermal energy from a single fuel source. The distributed generation nature of the technology also has the potential to reduce losses due to electrical transmission and distribution inefficiencies and to alleviate utility peak demand problems. However, the technology competes with other supply options such as innovative central electricity generation and heat pump technologies and – for renewable

energy – solar thermal and photovoltaic systems and biomass heating systems.

A number of studies deal with building-integrated cogeneration systems and their environmental and economic performance in comparison with other supply options. Selected papers are referenced in Section 3. There are also a wide range of techniques for modelling and assessing the performance of MCHP technologies [1], based on a variety of basic modelling aims; from economic assessments [2] through to studies of the impact on national electricity distribution networks [3]. Modelling methods range from simple calculations using aggregate energy demand (several computer design tools are commercially available), through to multiple-objective optimisation approaches [4,5]. Even when focussing on energy and emissions evaluations of individual building-integrated MCHP systems, there are a wide range of levels in modelling detail and temporal resolution. The analysis of thermal energy utilization in buildings is complicated by strong coupling between the cogeneration unit, other heating, ventilation and air conditioning (HVAC) components, and the building's thermal and electrical demands. These system integration issues lead to the need for whole-building simulation programs to facilitate the analysis of residential cogeneration. The objectives of Annex 42 of the International Energy Agency's Energy Conservation in Buildings and Community Systems Programme (IEA/ECBCS) were to develop simulation models, calibrated by results from laboratory tests, that advance the design, operation, and analysis of residential cogeneration systems, and to apply these models to assess the technical, environmental, and economic performance of the technologies. As an extension of an earlier study which was based on simpler models and which considered two types of fuel cell systems only [6], a performance assessment study has been conducted within the framework of Annex 42 for a number of micro-cogeneration systems and residential buildings [7]. This paper outlines the methodology applied in this study, identifies important parameters influencing the performance of MCHP systems and evaluates, in terms of energy and emissions, a number of MCHP systems for several building types, occupant related loads and grid electricity mixes, and compares them to traditional condensing gas boiler and heat pump technologies.

2. Brief review of existing MCHP energy and emissions studies

A number of studies have investigated cogeneration systems integrated in individual buildings using whole-building and systems simulation tools and compared their environmental performance with other supply options. Both building types and grid electricity generation mix are of national, regional or even municipal character, and the results of performance assessment studies may vary accordingly. In the following, some typical studies are referenced, focusing on Central European countries when considering such regional factors. In the Belgian context, Voorspools and D'haeseleer [8] studied MCHP and mini CHP as well as the dynamic interaction between the cogeneration and central power systems [9]. Different types of MCHP were also studied by DePaepe et al. [10]. For Germany, Bruckner et al. [11] already showed that cogeneration offers considerable scope for energy savings on a municipal level. Lindenberger et al. [12] showed gas internal combustion engine (ICE) micro-cogeneration units to achieve cost savings and 20% (non-renewable primary) energy savings in comparison with a configuration with gas-fired condensing boiler and national grid electricity with the German electricity production mix. The technological and environmental aspects of building-integrated cogeneration are also covered by Entress [13] and, comprehensively, especially in terms of life cycle analysis and for fuel cells, by Pehnt [14–16]. The role and potential of fuel cell MCHP was summarized

in great detail in [17]. Boehm [18] comprehensively assessed the performance of PEMFC, and Sitré [19] evaluated SOFC and Stirling (SE) MCHP for low-energy single-family houses (SFH). The situation in Italy was studied e.g. by Dentice d'Accadia et al. [20] and Possidente et al. [21], with Sibilio et al. [22] extending their studies to also include residential trigeneration applications. For the Netherlands, Laag et al. [23] predicted PE savings of 12% (SE) to 24% (FC) for MCHP applications in an average Dutch household, and Ruijg and Ribberink [24] assessed profitability of PEMFC, SOFC and Stirling (SE) MCHP systems. For SE and fuel cell MCHP systems in UK SFH, Peacock and Newborough [25,26] predicted 9% and 16% of CO₂ emissions savings compared to condensing boiler and grid electricity, and even greater savings for higher power output systems of high efficiency, with larger portions of generated electricity being exported [27]. In several papers, Hawkes et al. examined the techno-economic aspects of MCHP [28,29] and related least-cost optimisation strategies [30], and also investigated the influence of temporal precision on the performance results [31]. A comparative CO₂ savings assessment of FC, SE and ICE MCHP and heat pumps for the UK domestic sector was made by Cockroft and Kelly [32]. The CO₂ reduction potential of MCHP in the Swiss context was evaluated by authors such as Rognon [33], although not on the basis of detailed building simulations.

Analyses of the combination of residential cogeneration systems with solar thermal systems confirmed that an overall increase in the contribution of renewable energy to meet energy demands was possible, but also identified conflicts between producing heat in residential cogeneration and with the solar thermal system [6,12]. Heat buffer storages may significantly enhance energy efficiency in MCHP systems [34].

Demand profiles for DHW and electricity for appliances and lighting are based on measurements [25,27], aggregated on the basis of probabilistic distributions for occupancy and for the individual components, or are generated using stochastic methods [23]. The topic of residential DHW and electric load profiles is covered comprehensively in [35].

Control strategies and modes were shown to have significant effects on energy and environmental system performance. In many cases, heat-following modes exhibited the best efficiency for energy, and electricity-following control modes for cost, but combined control modes were shown to be most effective in certain cases [36,37]. Cost control considering dynamic prices and emissions-optimized control strategies were developed and assessed by authors such as Vetter [38]. Base load control offered energy savings compared with peak load-oriented control [8]. Predictive control was analyzed, especially for SOFC systems where system shut-down jeopardizes reliability and service life due to thermal cycling degradation effects [6]. Fuzzy logic based control strategies were analysed by authors including Entchev [36].

The efficiencies of an MCHP system under real operating conditions can be considerably lower than those of the MCHP device alone when operating at full load. Start-up and shut-down cycles and thermal losses from heat storage were associated to such performance reductions for an SE device in a Canadian study [39].

MCHP modelling and simulations also form the basis for performance optimizations. To define sets of optimal configurations, sensitivity analysis [40] or multiple-objective (energy-economic or energy-environmental) optimization techniques were applied, also combining process flow models with process integration methods and multiple-objective optimization [4,5].

A more comprehensive overview of available studies and projects that cover the performance assessment of residential cogeneration systems in terms of environmental criteria, mainly primary energy demand and greenhouse gas emissions, was given in [41].

3. Methodology

The methodology concerning system modelling, boundary conditions, performance indicators and the evaluation procedure was established based on the methodology framework given in [42]. This study considered several main elements of this methodology. Dynamic system models were applied, calibrated by laboratory test results wherever available. These models include part-load characteristics, dependency on heat exchanger supply and return temperature and transient behaviour. Transient interaction with the building heat demand and heat distribution was fully considered. However, the net heating demand was the determining parameter, while the influence of passive gains (solar, day-lighting, internal gains) or of the climate on the space heat demand were not a topic of investigation. Energy management and system control were explicitly specified and regarded as important parameters influencing system performance. Occupant-related DHW and electric demand were specified as load profiles, considering different demand levels. The simulation analysis produced values for the net energy demand and, by simulating the building-integrated generation systems, the demand for delivered energy for the building. Primary energy consumption values were derived in a post-processing analysis, based on the calculated value for the demand of delivered energy. Further figures such as overall efficiencies were derived from these energy values. Further post-processing was applied to calculate emissions based on the energy demand values. Various evaluation cases and configurations were defined, modelled and simulated with the TRNSYS 16.1 transient building and systems simulation code [43]. The cases were simulated for a full year period with a time interval of 15 min unless otherwise stated.

3.1. Energy types considered

From the environmental standpoint, fossil and/or non-renewable energies have to be considered. Fossil energy is related to the emission criteria. The “renewable/non-renewable” aspect focuses mainly on hydro vs. nuclear power generation, and on the use of solar heat or electricity. Three types of energy were considered for the assessment of energy consumption: (i) net energy demand (part of the energy demand which is provided by the HVAC and the cogeneration system (including contribution of renewable energy systems and ambient sources) to cover the respective energy demands for space heating, domestic hot water and electricity, (ii) delivered energy (energy delivered to the building as fuel, heat or electricity), and (iii) non-renewable primary energy (NRPE) demand attributed to the delivered energy carriers, considering recovery, conversion in central power stations, storage and distribution. Embodied energies in the building energy system were not considered. NRPE values are differentiated by primary energy demand for delivered grid electricity and for the delivered fuel (natural gas).

For comparison purposes, the calculated delivered and primary energies were related to the energy reference floor area of the building. The energy reference floor area is based on external dimensions and considers all (also indirectly) heated spaces of the building. The energy values were thus expressed in MJ/m², or MJ/m²/a for annual periods.

3.2. Grid electricity

For grid electricity, the NRPE demand and respective CO₂-equivalent (CO₂-eq) emission values depend on the generation mix of the electric utility grid. Two grid electricity mixes were considered: The European mix according to the Union for the Co-ordination of

Transmission of Electricity (UCTE) as a reference for the existing grid, and a combined cycle power plant (CCPP) mix as the representative for an alternative marginal and innovative natural gas driven technology. For the CCPP, an electrical efficiency of 58% (in relation to the LHV of NG fuel), a factor of 13% for primary energy to plant losses according to the value for NG and a factor of 11.7% for grid distribution losses were assumed. No time dependency of the mix was considered. However, in reality, the electricity mix (and also electricity prices) may vary significantly between peak demand times and night time, resulting in quite different primary energy demand figures. This could be addressed in future studies.

3.3. Performance indicators

The systems were analysed for two performance indicators: (a) annual NRPE demand, and (b) respective emissions in terms of CO₂-eq. The values were calculated from the delivered energy demand using inventory data from version 1.3 of the Ecoinvent database [44]. The greenhouse warming potential was calculated applying the GWP(100a) methodology [45], and expressed in carbon dioxide equivalent emissions (CO₂-eq). The resulting primary energy and emission factors are given in Table 1.

Electricity exported to the grid was credited using the same conversion factors. The electricity exported was discounted by 10% to account for losses in transmission to the final user.

4. Building data and loads

4.1. Building types and geometry

Two building sizes were considered: a single-family house (SFH) and a multi-family house (MFH) with four dwellings. Three energy demand levels were specified for both building types (Table 2): low-energy building according to the Passive House standard [46] (labelled Passive House), building according to the present Swiss building code (labelled Building Code) [47], and the average Swiss residential building stock (labelled Building Stock) (values for existing buildings stated in [48]).

The geometric layout of the MFH is basically a multiplication of the SFH type building geometry. All dwellings have the same useable floor area (188.8 m²). The energy reference floor area is the sum of the floor areas of all heated or air conditioned rooms, based on the outer dimensions of the building including the exterior walls. The thermal properties of the building envelope (insulation and glazing), and the building equipment and appliances are adapted to the different energy levels of the buildings.

Table 1

Primary energy factors (ratio of primary energy to delivered energy) and CO₂-eq emission factors.

	Electricity mix for low-voltage electricity supply		Natural gas supply
	UCTE	CCPP	
Primary energy factor (based on LHV) (MJ primary/MJ delivered energy)			
Renewable primary energy factor	0.281	0.004	0.002
Non-renewable primary energy factor	3.260	2.290	1.190
Total primary energy factor	3.541	2.294	1.192
CO ₂ -eq emission factor (kg/MJ delivered energy)	0.149	0.129	0.011
CO ₂ -eq emission factor, including combustion (kg/MJ delivered energy)			0.067

Table 2

Energy demands per m² energy reference floor area derived from simulations, heat transfer coefficients (U-values) of exterior walls and glazing, and solar heat gain coefficient (G-value) of glazing of different building types.

Building energy demand level	Building Stock		Building Code		Passive House	
	SFH	MFH	SFH	MFH	SFH	MFH
Space heat demand (MJ/m ² /a)	516	518	172	154	66	47
Electricity demand (MJ/m ² /a)	51	68	54	67	47	64
U-value of exterior walls (W/m ² /K)	0.7	1.1	0.2	0.3	0.15	0.16
U-value of roof (W/m ² /K)	0.35	0.58	0.16	0.2	0.11	0.15
U-value of glazing (W/m ² /K)	2.8	2.8	1.4	1.4	0.7	0.7
G-value of glazing (–)	0.76	0.76	0.59	0.59	0.59	0.59

Table 3

Heat distribution and ventilation for individual building types.

Building type (Acronym)	Heat distribution	Ventilation
Building Stock	Water-based radiators/convectors (27% radiative)	Natural ventilation by window airing (2.1 m ³ /h/m ²)
Building Code	Floor heating, similar to concrete core cooling/heating	Natural ventilation by window airing (0.7 m ³ /h/m ²)
Passive House	Floor heating, similar to concrete core cooling/heating	Mechanical balanced ventilation with heat recovery, (heat recovery efficiency: 68%) (120 m ³ /h per dwelling) 0.1 h ^{−1} infiltration in zones with external doors

The assumed heat distribution and ventilation systems for the individual building types are described in Table 3 (similar for SFH and MFH).

4.2. Building loads

4.2.1. Space heating loads

The basic link between the building and the cogeneration system is given by the time-dependent space heating load of the building. In the simulation, the space heating loads were determined using the TRNSYS multi-zone building model Type 56. The interaction between the building, HVAC and cogeneration system, heat distribution system and the time-varying boundary conditions was fully considered. The net heat demand is the determining parameter, and different levels were accounted for by the selection of building types. The influence of different climates on the heat demand was not analyzed. Simulations were performed for one geographic location (Basle, Switzerland).

4.2.2. Internal and external heat gains

Heat (100%) from electrical appliances, lighting and occupants was assumed to contribute to the internal load. These gains were distributed to the individual rooms using a fixed distribution scheme, also considering results of the earlier study [6], where the electricity demand for artificial lighting was calculated considering the availability of daylight. External gains were calculated with the TRNSYS building model. Solar protection (60–80%) was applied with due consideration of daytime lighting requirements. Excessive indoor air temperatures in summer were reduced by increased natural ventilation.

A part of the parasitic losses of the MCHP device (radiative and convective skin losses including venting of heat from individual MCHP components for cooling purposes) may contribute to the internal heat gains of the building and thus reduce heating load or increase cooling load. In this study, these gains are not considered as the systems are assumed to be located in unheated rooms.

4.2.3. Domestic hot water (DHW) demand profiles

For the SFH, the medium domestic hot water (DHW) demand profile at 200 l per day, heated from 10 to 45 °C, at 15 min intervals, specified within IEA Annex 42 [35] was used (equivalent to annual net energy demand of 50 MJ/m²/a). To study the influence of the load level, two additional load levels (low and high) were considered (corresponding to 100 and 300 l per day for DHW, or 25 and 75 MJ/m²/a, respectively). For the MFH, the DHW profile for higher demands (800 l per day) issued by IEA SHC Task 26 [49] was used.

4.2.4. Occupant-related electricity demand profiles

For the SFH, the European electric medium demand profile at 5 min intervals specified in IEA Annex 42 [35], was used (equivalent to an annual energy demand of 54 MJ/m²/a). To study the influence of the load level, two additional load levels, also specified in [35], were considered, low (21 MJ/m²/a) and high (150 MJ/m²/a). For the MFH, the electric load profile was generated by the superposition of 1 low demand, 2 medium demand and 1 high demand SFH profiles.

4.2.5. Further energy demands and losses

The electricity demand of the pumps for the heat distribution within the building analyzed is assumed to be quite similar for both the cogeneration and the reference systems. As the focus in this study is the comparison of the performance of the cogeneration device with the reference systems, this electricity demand was not considered. This has to be taken into account when an overall assessment of energy conversion and the heat distribution system is made. Heat losses for space heating distribution are also not considered. For domestic hot water, it is assumed that the heat demand equals the net energy to heat the water (no distribution losses assumed).

5. Systems analyzed

The systems analysed basically comprise an energy conversion device (MCHP device and auxiliary gas boiler), one combined or two separate storage tanks for heating and domestic hot water, pumps and valves, and the control system. Fig. 1 shows the schematics of the system configurations analyzed in this study.

All of the MCHP devices analysed are fuelled by natural gas. The generated electricity is used directly in the house or is exported to the electric grid. The electric grid is also used to cover peak demand. The auxiliary gas boiler was assumed to cut in automatically if additional thermal power was needed.

All cases were controlled in heat-following mode, with temperatures in the heat storage tank(s) as the main control parameters. The storage temperature level was controlled with a proportional-integral (PI) controller. An individual heating curve (space heating demand vs. outdoor air temperature) was determined for each building. A setpoint for storage loading, established on the basis of this curve and the 24 h average outside air temperature, was used by a PI controller with anti-wind-up functions to define the actual heat generation of the MCHP and/or the gas boiler system. In cases with non-modulating devices, 2- or 3-point controllers have been used.

Given the adverse effects of start/stop operations on today's SOFC systems in terms of material deterioration, lifespan and maintenance cost, continuous operation was envisaged for the SOFC system.

5.1. MCHP devices

MCHP prototypes and commercially available devices tested in the empirical evaluation cases of Annex 42 [50] were considered

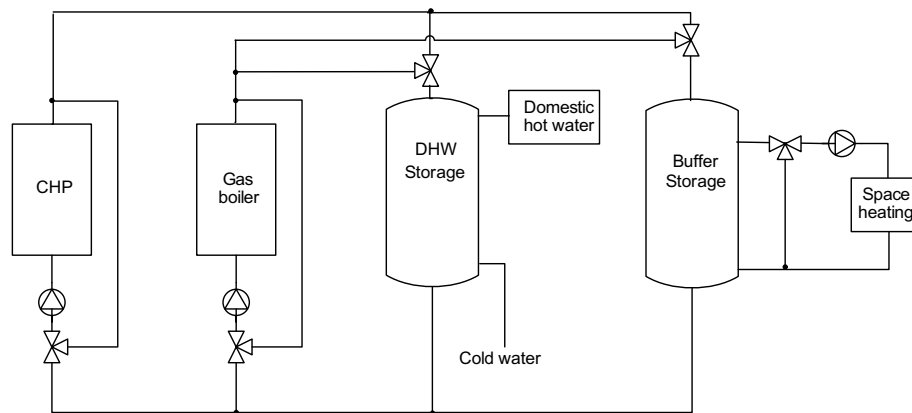


Fig. 1. Schematics of investigated systems.

with priority in this study. The detailed dynamic Annex 42 models [51] were used to model the MCHP devices wherever the required data was available. Otherwise, performance map models were established, accounting for MCHP outlet flow temperature level.

5.1.1. Solid oxide fuel cell (SOFC)

The modulating SOFC device considered has a nominal rating of 1 kW electric and 2.5 kW thermal power output. The detailed dynamic fuel cell model developed in Annex 42 [51] was used. Measured data of an actual SOFC prototype device have been used to calibrate the model parameters. However, after the calibration, the electrical efficiency was improved to maximum 35% (LHV), a level the manufacturer of the SOFC device expects to be realistically achievable with the next generation device. The model therefore adjusts thermal efficiency accordingly. A modulation range from 480 W to 1 kW electrical power output was assumed. The change in modulation from one time step to the next was not restricted. This implies a maximum power output change of at least 0.6 W/s, a value probably too high for current prototypes. The same SOFC device was assumed to be installed in the SFH as well as in the MFH buildings. In the SFH, the system is shut during summer period.

5.1.2. Polymer electrolyte fuel cell (PEMFC)

The modulating PEMFC device considered has a nominal rating of 4.6 kW electric and 7.0 kW thermal power output and maximum efficiencies (LHV) of 27% electric and 93% total. A simple performance map approach has been used to model the PEMFC device. However, the model was calibrated using experimental data from a prototype PEMFC unit, gained in IEA Annex 42 [50] (Fig. 2).

5.1.3. Stirling engine (SE)

The engine for the SFH (SE 1) has a rating of 0.75 kW electric and 7.0 kW thermal power output, maximum efficiencies (LHV) of 9.3% electric and 82% total, and was run in on-off mode. The Annex 42 model for combustion-based MCHP devices [51] was used, calibrated with data from laboratory tests performed in Annex 42 [50]. For the MFH, the modulating engine (SE 2) has an output range of 2.0–9.5 kW electric and 8.0–26.0 kW thermal power, maximum efficiencies (LHV) of 24% electric and 96% total. A performance map model with manufacturer data for a commercially available device was used.

5.1.4. Internal combustion engine (ICE)

The modulating internal combustion engine for the SFH (ICE 1) has an output range of 1.3–4.7 kW electric and 4.2–12.5 kW thermal power, and maximum efficiencies (LHV) of 25% electric and

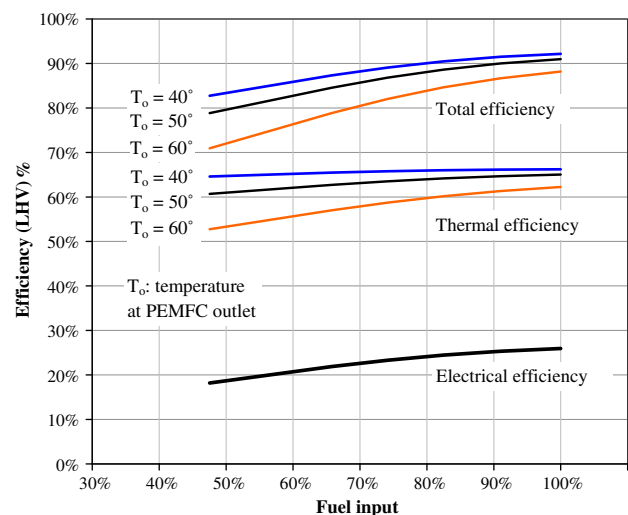


Fig. 2. Electrical (AC to grid), thermal and total efficiency performance characteristics of 4.6 kW PEMFC device.

94% total. A performance map model calibrated with data from laboratory tests performed in Annex 42 [50] was used. The engine for the MFH (ICE 2), running in on-off mode, has a rating of 5.0 kW electric and 14.6 kW thermal power output, and maximum efficiencies (LHV) of 26% electric and 89% total. The Annex 42 model for combustion-based MCHP devices [51] was used, calibrated with data from laboratory tests performed in Annex 42 [50].

5.2. Hot water storage tank

For buildings with low-temperature floor heating, separate tanks for DHW and the space heating buffer storage were assumed. For buildings with high-temperature radiator heating, and for all SFH with the non-modulating SE system, a combination storage tank was assumed. All storage types and sizes were modelled as stratified storage units and were specified as cylindrical storage tanks with rock wool insulation of 8 cm (thermal conductivity 0.04 W/m/K).

5.3. Reference systems

Two reference systems with grid electricity supply and two types of heat generation were considered:

5.3.1. Gas boiler

State-of-the-art gas boilers, condensing and modulating in a wide range, were used for the reference cases and as back-up/auxiliary heaters in the MCHP systems. The lowest modulation power and nominal power were adapted to the different buildings (Table 4), but the efficiency characteristics (depending on return flow water temperature and load) were similar in all applications. The characteristics were based on manufacturer data of commercially available products. Dynamic thermal effects in relation to the thermal capacities of the boiler and water circuit involved were not considered.

5.3.2. Ground-coupled heat pump

A heat pump with a rated heating power of 6.0 kW was considered. The COP characteristics of the heat pump for different heat source temperatures (at entry to evaporator) and supply temperatures are based on manufacturer data and were used for the performance map model of the heat pump. The heat pump system was not analyzed for the Building Stock building type.

In order to correctly reflect the energetic interaction of the heat pump and the ground, a dynamic ground storage model is used. The model by Wetter and Huber [52] was used. For the Building Code building, a borehole of 100 m depth in dry soil/sand with a

32 mm diameter double-U pipe was assumed. Brine flow was 0.4 kg/s. The electricity demand of the brine pump (120 W) accounts for approximately 7% of heat pump electricity demand. For the other buildings, the heat output of the bore-hole heat exchanger was scaled up or down according to the heat demands for the building analyzed.

6. Results

6.1. NRPE demand

For the European (UCTE) electricity mix, most MCHP systems offered reductions in NRPE demand, except for the SE 1 system in the Building Code SFH and Passive House SFH building due to the low electric and overall efficiency of this SE device (Fig. 3). Maximum reductions were achieved with the ICE 1 device in the Building Stock SFH building (34%), the SOFC system in the Building Code SFH building (27%), and with the SE 2 device in the Building Stock MFH building (24%). It has to be noted that all these reductions are also an effect of surplus electricity generation, which is considered as a bonus and was thus subtracted from the primary energy demand associated with the delivered energy to the house. However, systems with no surplus electricity generation also provided reductions of >10%.

For the CCPP mix, by far the largest NRPE reductions resulted for the heat pump systems (up to 29%). The maximum reduction with a MCHP system was achieved with the ICE 1 system in the Building Stock SFH (14%), and with the SOFC system in the Building Code SFH building (12%). Again, both systems generated a surplus of electricity. Conversely, the SE systems in the Passive House SFH and the Building Code SFH buildings lead to a small increase in NRPE demand.

The increase for the SE 1 system in the Passive House and Building Code SFH can be attributed to the low thermal and the low electrical efficiency of the device. Conversely, the same SE device

Table 4
Lowest modulation power and nominal power of gas boilers used for different buildings.

Building type	Building Stock		Building Code		Passive House	
	SFH	MFH	SFH	MFH	SFH	MFH
Lowest and nominal power (kW)						
Reference cases	2.0–12.6	10.6–50.4	0.9–9	10.6–50.4	0.9–9	0.9–9
Back-up heater for MCHP systems	0.9–9	10.6–50.4	0.9–9	2.0–12.6	0.9–9	0.9–9

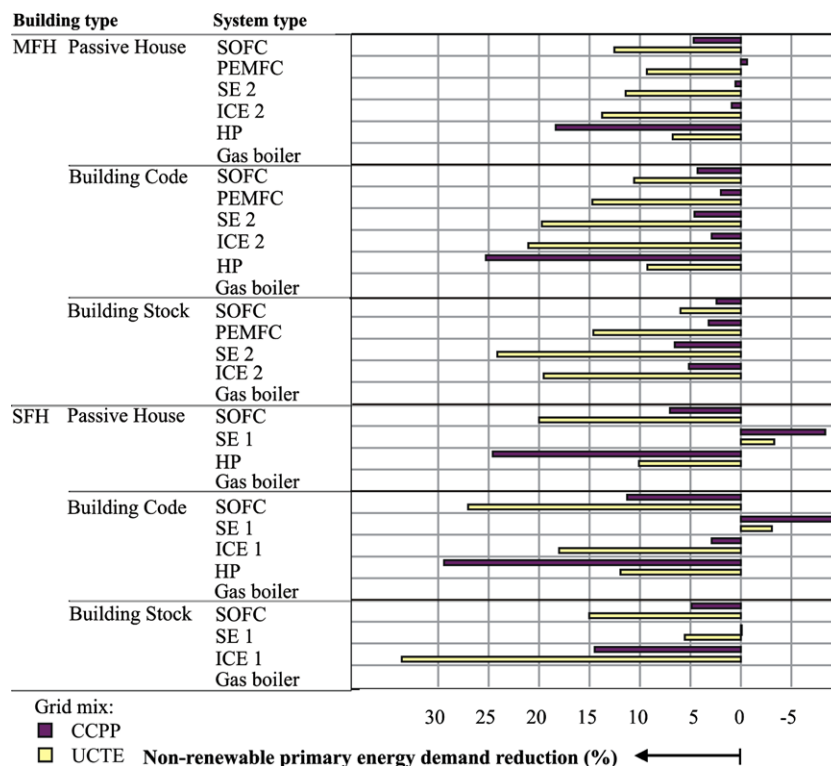


Fig. 3. Reduction in annual NRPE demand compared with condensing gas boiler reference system for cogeneration systems and grid electricity mixes considered.

gave a small NRPE reduction in the Building Stock SFH. This house has a high-temperature heat distribution system, for which the thermal efficiency of the reference GB system is also lower, as there was no possibility for flue gas condensation. Large reductions resulted for the SE 2 device in the MFH buildings because this device has relatively good overall and electrical efficiency.

6.2. Emissions

The comparison in terms of CO₂-eq emission was, as expected, highly dependent on the grid electricity emission factor. Most MCHP systems offered reductions for the UCTE electricity mix (up to 22%, for the IC 1 in the Building Stock SFH), (Fig. 4). However, maximum reductions resulted for the heat pump system (23%). For the CCPP mix, maximum reductions were again achieved by far with the heat pump systems (up to 29%). Maximum reductions with a cogeneration system were achieved with a SFH ICE 1 system in the Building Stock (14%) and the SOFC system (11%) in the Building Code SFH.

6.3. Part-load operation and load duration curves

Fig. 5 shows the histogram of part-load (modulation) ratios for the SOFC system in the six buildings. In the SFH buildings, the SOFC system ran at part-load for a significant period of time. In the MFH buildings, the system more or less either ran at full load, or was operated at minimum power.

This is due to the fact that the capacity of the SOFC is too low for the MFH buildings. This is also clearly visible in the duration curves for heat loads and system heat output given in Fig. 6. The figure also illustrates the balancing effect of the heat storage, allowing

the heat output curve to deviate significantly from the load curve.

6.4. Influence of DHW and electricity demand level

Fig. 7 compares NRPE demand reductions in the Building Code SFH equipped with SOFC system with the gas boiler reference system for a number of different combinations of DHW and electricity demand levels, specified in Section 5.2, and considering a UCTE mix. The results show that NRPE demand was always lower for the SOFC system. Higher reductions result for higher loads. However, the difference in demand decreases again at very high loads when the (auxiliary or back-up) gas boiler and grid electricity supply become dominant in the SOFC system.

6.5. Influence of plant size ratio (MCHP heat output to building heat demand)

The influence of annual thermal output of the MCHP device was investigated in relation to the total annual building heat demand (for space heating and DHW). MCHP capacity was scaled (scaling factor = 1.0 means the simulations with the performance data of the original device as used in the basic cases). For simplification, the efficiency characteristics of the MCHP device relative to the scaled capacity were kept unchanged, although larger systems normally have better efficiencies.

Fig. 8 shows the relative savings in NRPE demand for the PEMFC system, compared to the gas boiler reference case, for the two electricity mixes. The results showed that the optimal ratio of annual thermal output of MCHP device to annual building heat demand was dependent on the electricity mix and on the

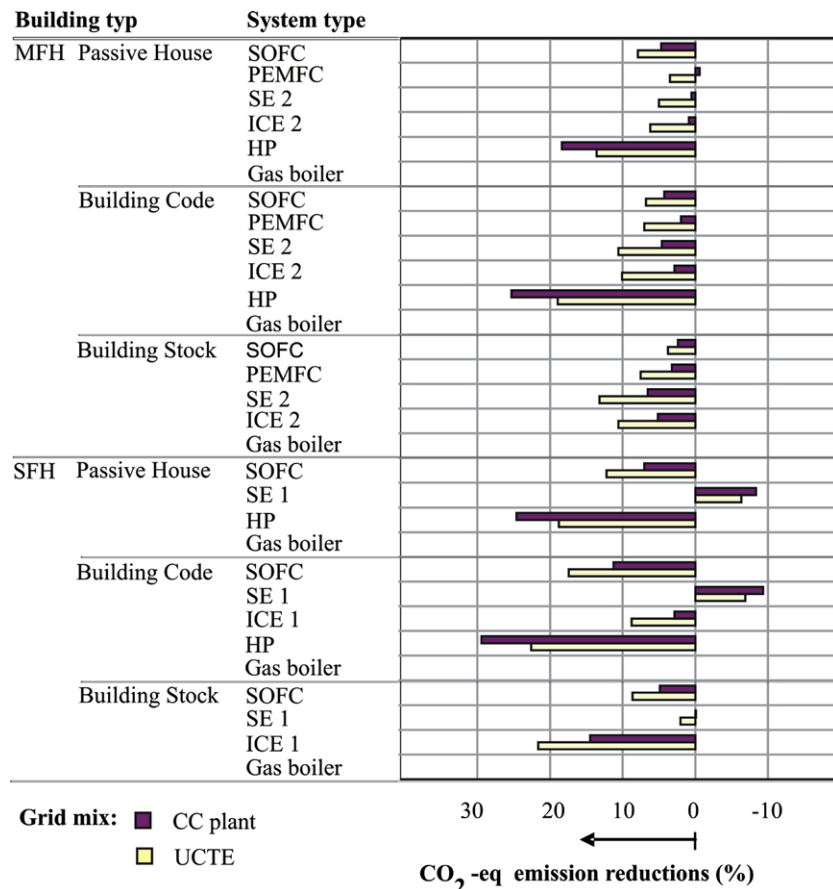


Fig. 4. Reductions of annual CO₂-eq emissions compared with condensing gas boiler reference system for cogeneration systems and grid electricity mixes considered.

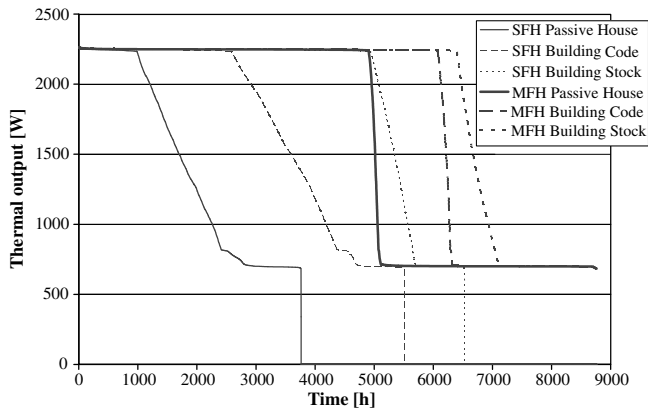


Fig. 5. Histogram of part-load (modulation) ratios for SOFC system for six building types considered.

characteristics of the electric efficiency curve of the MCHP device. While the optimal ratio for the PEMFC depending on the electrical mix was between 0.7 and 0.9, for the SOFC, values of roughly 0.8 resulted for the CCPP mix and 1.3 for the UCTE mix. This is because the optimum electrical efficiency of the SOFC device is at part-load. A larger device, operating for a longer period at part-load, is therefore more favourable than a smaller device, even if

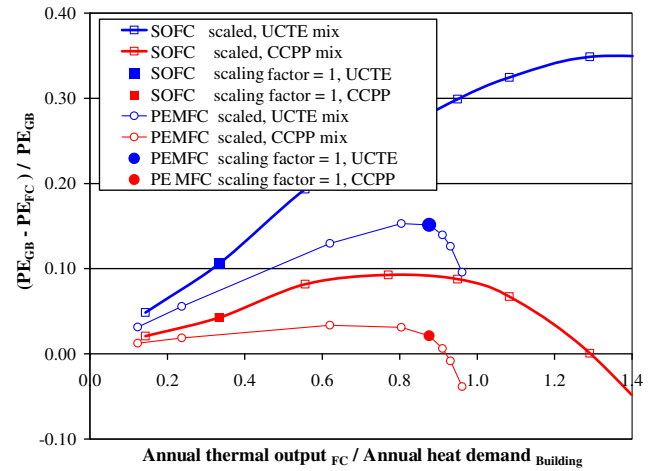


Fig. 8. Difference between NRPE demand of building equipped with fuel cell system (PE_{FC}) and demand of building with reference gas boiler system (PE_{GB}), weighted with PE_{GB} , as a function of the ratio of annual thermal output of fuel cell system to total annual heat demand of building, for UCTE and CCPP electricity mix.

some of the generated heat has to be dumped at certain times. The opposite is true for the PEMFC, where the highest electrical efficiency is at full load.

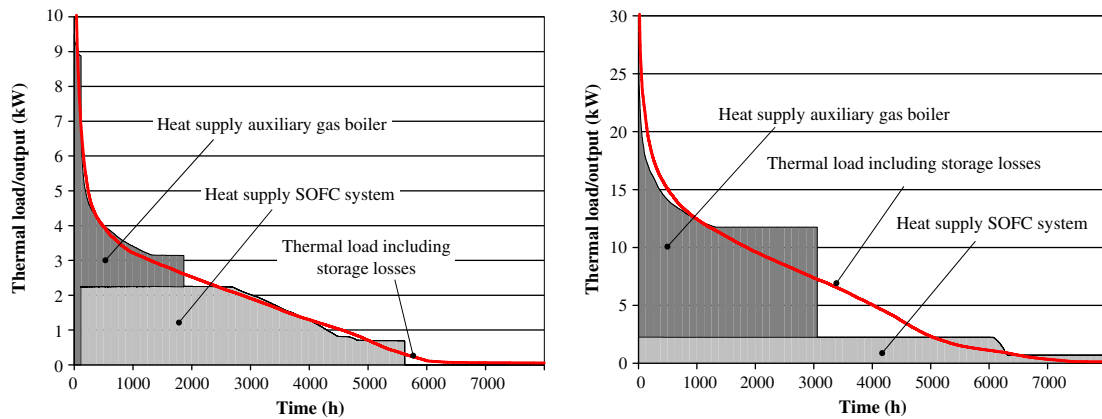


Fig. 6. Thermal load and heat output duration curves for the SOFC system in Building Code types SFH (left) and MFH (right).

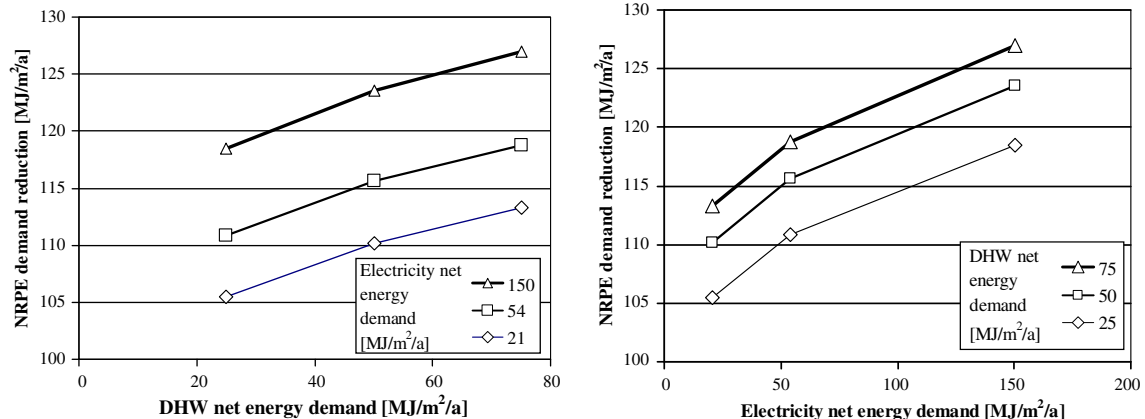


Fig. 7. NRPE demand reduction for Building Code SHF (space heat demand $170 \text{ MJ/m}^2/\text{a}$) equipped with SOFC system compared with condensing gas boiler reference system, for several combinations of DHW and electric demand levels. UCTE electricity mix.

7. Conclusions

In this paper, a methodology for assessing the performance of natural gas-fuelled building-integrated cogeneration (MCHP) systems in terms of primary energy demand and CO₂ emissions was outlined and demonstrated for a number of residential building types and occupant driven loads. To assess the potential energy and emissions savings attributable to the MCHP system, simulation models were applied which fully account for: (i) the transient nature of building and occupant driven loads, (ii) the part-load characteristics of the cogeneration system and the interaction between the loads and the system output both in terms of energy and temperature levels, (iii) system energy management and control, and (iv) boundary conditions especially in terms of grid electricity mix.

For the European electricity grid mix, most MCHP systems offered NRPE demand reductions compared to the reference condensing gas boiler system. For the CCPP electricity generation mix, the largest NRPE reductions resulted for the ground-coupled heat pump systems, although cogeneration systems also showed reductions. No reductions resulted for MCHP devices with low thermal and electric efficiency and no provisions for flue gas condensation in the heat exchanger. The study revealed that, in certain circumstances, MCHP systems can significantly reduce primary energy consumption and CO₂ emissions relative to conventional means of supplying heat and power, but that MCHP systems face a strong competitive situation with other innovative supply options like heat pump technologies with CCPP-based electricity generation. It was shown that the MCHP device has to be correctly dimensioned in accordance with the heat loads in order to fully exploit the reduction potential. However, this might prove difficult, as there is no range of MCHP products with different capacities available on the market. The strong dependence of the achievable energy savings and, to an even greater extent, of the resulting CO₂ emission reductions on the grid electricity generation mix was confirmed. The plurality of electricity mix situations at national or regional level makes it difficult to draw generally valid conclusions on the application potential of MCHP systems. Here, only average primary energy and emission factors were employed. Computing the actual savings would also require knowledge of the actual (time dependant) electricity generation mix.

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